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An Efficient Waste-To-Energy Model in Isolated Environments. Case Study: La Gomera (Canary Islands)

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Abstract: Municipal solid waste (MSW) management is a controversial aspect of isolated environments, not only because the production of waste grows exponentially, but also because in these isolated regions the difficulties are accentuated in comparison with the mainland territories. The limitation of space, the technology of scale and the peaks of generation due to existing tourism, are clear examples of the barriers that must be overcome. This research studies the potential of MSW recovery on the island of La Gomera (Canary Islands) as an alternative to landfill deposition, being an additional energy source for heat and electricity. Likewise, the possibility of carrying out the landfill mining located in the El Revolcadero environmental complex is explored. The methodology followed consists, first of all, on estimating the annual amount of MSW and waste deposited in the landfill. Second, the characterization of representative samples of each municipality is carried out. Third, according to these characteristics, the thermal treatment is chosen and, finally, the energy generated is evaluated. The results are encouraging, and many advantages are derived from this model. The annual recycling figure increases by about 5000 tons per year, the percentage of renewable energy from waste reaches 35.5% (most installed capacity is diesel), and greenhouse gases (GHG) are reduced by more than half. To overcome the challenges in the integral management of MSW, it is necessary to move from a linear economy to a circular economy that takes into account the priorities established by the European Union to solve the problem of these isolated environments in terms of energy.

Keywords: waste-to-energy; isolated environments; circular economy; waste management; carbon emission reduction; Canary Islands

1. Introduction

1.1. Motivation

Landfills are one of the most important sources of gas emissions. These emissions are known to contain mainly methane (CH_4) and carbon dioxide (CO_2), both considered greenhouse gases that contribute to global warming [1]. The amount of municipal solid waste (MSW) generated each year and the numerous actors and bodies involved in this complex process are issues that require detailed study, to propose effective practical measures to improve their management. Cities are undergoing a critical situation owing to the increasing amount of solid waste they generate and the resulting growing demand for new sites for final disposal. In view of this situation, diverse treatment technologies continue to be evaluated [2–4]. In this sense, Expósito and Velasco [5] analyze the efficiency of the Spanish regions in the development of the recycling market through the application of data envelopment analysis. They also take into account the requirements established by the European

Union and the Spanish legal framework regarding the priorities of waste management: reducing combined municipal solid waste and increasing the selective collection of recyclable materials [6,7].

There are many technological options available to reduce the waste generated [8]. The most usual procedures require thermal treatment (incineration, pyrolysis, gasification or plasma). However, other technologies have also been explored. Those based on anaerobic digestion and others that value waste, 'valorizing' it as an alternative fuel in thermal power generation installations. One of the most commonly considered options to reduce MSW is incineration or combustion. Indeed, one of the arguments used to seek support for incineration is that it generates energy that is presented as renewable. Poletto and Da Silva [9] argue that the controlled combustion of MSW is a definitive solution to the problem, when carried out in facilities with adequate air-pollution control devices. However, the reality is that it is necessary to attend to factors other than just air pollution, for example: impacts on water, soils, landscape, ecosystems and the urban areas themselves. In this context, sustainability consists of the evaluation of the environmental, economic and social impacts of the available waste treatment options [10]. In this sense, Cucchiella et al. [11] analyze a specific case in the Abruzzo region (Italy). The results are encouraging: the percentage of energy recovery in the treatment of municipal waste reaches values between 21% and 25%. In addition, it is possible to reduce emissions by about 55,500 tons of CO_2 per year. However, in this study it is pointed out that, although sustainable management of these power generation plants is possible, their implementation requires social approval.

Furthermore, the generation of electricity, heat or biofuels from renewable energy sources has become a priority in energy policy strategies on a global scale [12]. According to Nijkamp and Kourtit [13], cities consume 75% of the energy produced worldwide and generate 80% of CO_2 emissions; so it makes sense to try to reduce the emission of gases from residues by using them to generate energy. In this context, waste has been identified as an environmentally friendly energy source. Its utilization is considered an effective method to reduce the total emission of gases into the environment [14]. Seen in this way, the waste to energy (WtE) concept encapsulates an excellent opportunity to face two important current problems: on the one hand, the generation of energy from less polluting sources and, on the other, valorization of solid waste that otherwise accumulates in expensive landfills.

Finally, as explained by Brunner and Rechberger [15], the objectives of waste management range from the protection of men and the environment, to the conservation of resources such as materials, energy, and space. To achieve these objectives, WtE technology contributes in different ways: in addition to recovering energy (although it sometimes represents only a small percentage of the local demand of a region), it prevents organic hazardous waste from entering the environment and concentrates heavy metals in small amounts of waste. Moreover, integrated into a smart grid, the waste-to-energy technology can contribute positively to a power supply with low carbon content, reducing emissions of greenhouse gases.

1.2. Objectives

The objective of this study is to propose an efficient alternative in isolated environments, such as the Canary Islands. With the available data, we start from a concrete situation that the authors consider appropriate for study and improvement. The aim is that this study should serve to extrapolate the model to other isolated environments. According to the line of action marked by the European Union [6], a triple improvement is sought in the current waste management of the island: recover land destined for landfill (to regenerate green spaces), generate electricity through energy recovery and reduce CO_2 and CH_4 emissions. In this direction, according to what has already been mentioned, the priority objectives in waste management operations cannot be ignored [16]: (1) foresee and reduce the generation of waste; (2) simple reuse, in which the concept of circular economy plays a key role; (3) recycle; (4) valorize and take advantage of waste to obtain energy; and (5) take to landfill.

1.3. Structure of the Article

This article analyzes the current problems of municipal solid waste management (MSWM) for the case study of the island of La Gomera, in the Canary archipelago. First, a review of the literature is made on some issues on waste management and its valorization technologies in isolated territories. Second, a contextualization is made and the most relevant data about La Gomera island are presented. Third, the methodology used to approach the study is described. Fourth, the results of the study are presented. Fifth, the results of the study about waste management and valorization are discussed, and finally, some conclusions and recommendations are presented.

2. Municipal solid waste in Insular Electric Systems (IES): Canary Islands

2.1. The Management of Municipal Solid Waste

The evolution of waste management is a matter of vital importance in the strategic planning of a country. In fact, due to the growing trend of municipal solid waste generation, it is considered that its management is a problem of vital importance that affects the economies of developed and developing countries [17]. According to the traditional literature, increases in the generation of waste are associated with the growth of the economy, a greater industrialization, the increase in population and an increase in the standard of living [18]. In isolated environments such as the Canary Islands, it is also important to bear in mind that this increase in the generation of waste is due to the increase in the number of tourists visiting the islands.

The collection of waste is a key element of the waste management system. The absence of an adequate waste collection system completely interrupts the flow of waste management and the waste generators resort to illegal and undesirable practices such as dumping in prohibited sites [19] or the burning and disposal of waste in inappropriate places and lacking any control. In the Canary IES, this happens and produces negative effects for the environment and presents health hazards due to the generation of toxic emissions during the combustion and the spread of diseases caused by illegal dumping. Although in some of the islands such as Gran Canaria or Tenerife, the infrastructure is minimally developed, this does not happen in the rest of the islands, where the roads are too narrow or inaccessible, the collection vehicles are obsolete or the areas where waste is disposed of is nothing more than piles of waste that grow day by day.

2.2. Composition of Waste in the Canary Islands

In addition to the generation of waste, its composition is important in the search and development of strategies for waste management. From the data on the composition of waste, the indexes of recyclability, combustibility or biodegradability of waste streams can be identified. With these data, it is possible to make better direction in the design and implementation of appropriate technologies for the treatment of waste. Figure 1 shows the composition of the MSW of the Canary Islands.

2.3. Waste Treatment Technologies

In the case of the Canary Islands, there are not so many technologies that can be used to manage waste in the islands. Due to the volumes of waste that are handled, some thermochemical processes such as incineration or plasma are not suitable, because in the current state of the art they are profitable for larger amounts of flows. Along with this and the characterizations made by the Government of the Canary Islands (see Figure 1), it seems that taking into account the high content of organic matter, composting and aerobic digestion could be good solutions for waste management. Additionally, the high fraction of recyclable materials implies that the use of energy recovery technologies (WtE) can be considered.

In this regard, many authors claim that torrefaction can be an interesting pretreatment to reduce the high moisture content and the heterogeneous nature of the biomass to be valorized [21–24]. Batidzirai et al. [22] claim that torrefaction is a promising technology for pretreatment of biomass energy, with the potential to make an important contribution to the commercialization of biomass as a renewable energy resource. However, there are still many challenges, especially for isolated environments where operating conditions present more difficulties. In this sense, the drawbacks include: first, that the bulk density of the roasted material makes it difficult to transport and store it from an economic point of view. The second drawback arises as a solution to the previous problem, densification into pellets (energy pellets). According to Svanberg and Halldórsson [24], it is a challenge to achieve that this process combines an adequate efficiency with an acceptable energy consumption and acceptable wear of the used tools. Third, the waste flows of the particular case being studied are too small to combine these elements and make this intermediate process profitable.

2.3.1. Landfill Deposit

The landfill deposition consists in definitively eliminating the residues on the ground without taking advantage of them. It is the least desired option according to the waste management hierarchy [25]. However, due to the absence of more advanced techniques in waste management and the fact that landfills are the low in price option for waste [26], it is the option that prevails in the Canary archipelago.

Even though landfills represent the cheapest way to eliminate waste, it does not contribute anything in the value chain. That is to say, neither take advantage to obtain energy (waste-to-energy, WtE) nor to transform waste into other materials (waste-to-material, WtM), like recyclable materials, which can be used again. As explained by Mohee et al. [17], there are numerous cases of small isolated territories from where the Canary Islands can learn. For example, at the Mare Chicose landfill on the island of Mauritius, waste is eliminated in cells with double high density polyethylene lining, leachate handling, final cover and surface and underground water, where it is possible to generate 3.3 MW of electricity from landfill gas [27,28].

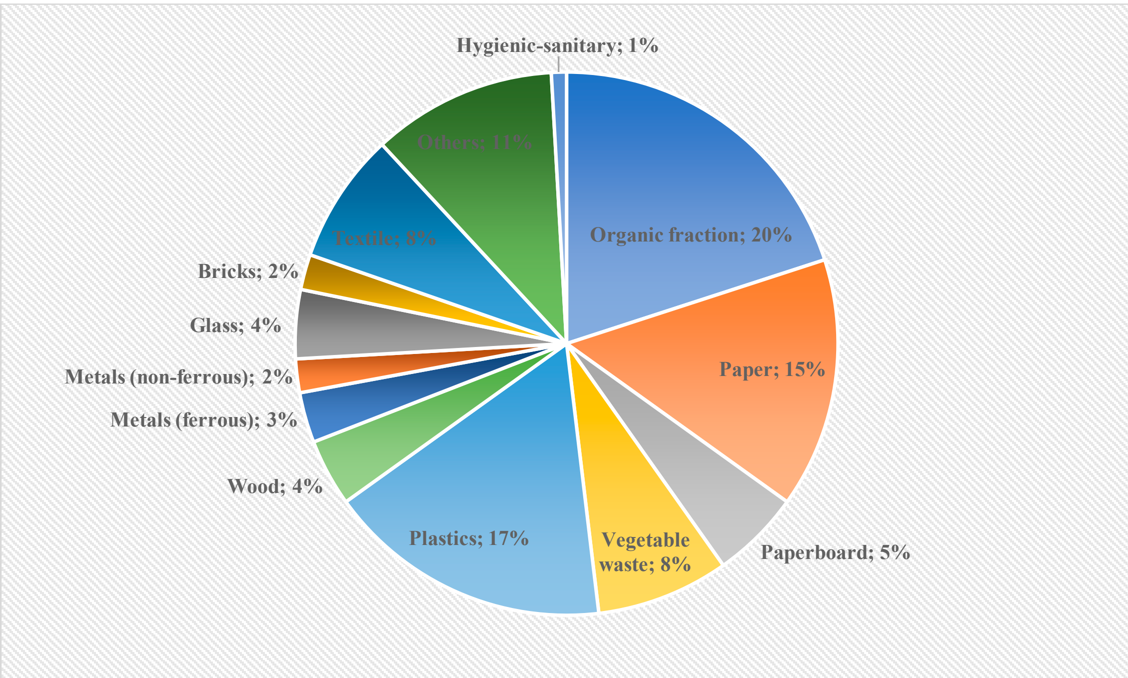

Figure 1. Composition of Canary Islands waste. Source: [20].

2.3.2. Recycling

The recycling activity is one of the most desired alternatives according to the current waste hierarchy. However, in the Canary Islands its development is deficient. There are many causes that can be attributed to this fact: (i) the low level of awareness, awareness and training of the population and of the authorities; (ii) the type of technology required to perform the collection and pre-processing methods; (iii) the lack of investment and technology at the scale required to develop efficient systems; and (iv) the value that waste can have with an adequate treatment (separation, reuse or recovery) is unknown and large quantities are not available in certain islands.

As already mentioned, in the Canary Islands IES the percentage of recycling is low due to the population and economic development, which is relatively small, and also due to the lack of education and awareness of the population in these matters [29]. Furthermore, what McDevitt [30] explains about the British Virgin Islands can also be applied to the Canary archipelago: there are islands where it is difficult to reach minimum recycling values due to the lack of space to store recyclable materials, as there are many protected areas and declared natural heritage sites. Finally, we cannot forget the barriers related to the transfer of technology and the limited economies of scale, which in these islands are an obstacle that must be taken into account.

2.3.3. Thermochemical Processes

Among the different well-known thermochemical processes, namely, incineration, pyrolysis and gasification, incineration, which is also called combustion, is the most common technology. Incineration is the thermal degradation and decomposition of waste in the presence of oxygen to produce CO_2, H_2O and heat at a temperature of 800–1000 °C [31], while pyrolysis is the decomposition of organic materials in the absence of oxygen at approximately 400–1000 °C, which results in liquid (bio-oil), gaseous and solid products (charcoal) [32,33]. On the other hand, gasification is the partial combustion of waste at approximately 800–1000°C to form a combustible gas mixture [31,34].

Torrefaction is a mild pyrolysis process carried out at 200–300 °C under inert conditions. In addition, when it is densified through pelletization, it translates into a denser product in energy (torrefied granules), with properties similar to coal [35]. As Chew and Doshi point out [21], the definition of torrefaction is commonly associated with roasting, mild pyrolysis, slow pyrolysis, and thermal pretreatment, according to its utilization.

Among the three thermochemical processes, in the Canary Islands incineration is performed only at a very localized level. In addition to not being profitable, uncontrolled burning is not beneficial in the Canary Islands' IES due to the high moisture content of the waste and the release of harmful substances. However, gasification can be a profitable process that contributes with a new energy framework in the Canary archipelago.

2.4. Greenhouse Gas (GHG) Emissions in the Waste Treatment and Disposal Sector

The Canary Islands require special comments regarding the waste sector. Their emissions could be classified as resulting from an induced environmental impact, due to greater waste management and therefore less overall environmental impact. However, this in turn implies greater localized methane emissions produced by the decomposition of buried organic waste. Its rapid growth has induced this sector to acquire significant weight within the total emissions, which arouses great interest from the energy point of view in the face of the current shortage and scarce energy use of recovered methane. Similarly, a phenomenon that needs control is the proliferation of illegal landfills locations where large quantities of waste are deposited without being controlled. In this regard, Quesada-Ruiz et al. [19] studied the mapping and characterization of illegal landfills in the islands of Gran Canaria and La Palma, identifying 286 and 153 illegal landfill locations, respectively.

Table 1 (based on [36]) shows the evolution of emissions in the waste treatment and elimination sector in the Canary Islands. By far the most important activity is clearly landfill disposal, contributing 93.5% of the total emissions by the sector in 2016).

Table 1. Evolution and contribution of GHG emissions in the Canary Islands, according to waste treatment and disposal activity.

Year	Landfill Deposit		Biological Treatment of MSW		Incineration		Sewage Treatment		Others		Total
	Gg CO_2-eq	%	Gg CO_2-eq	%	Gg CO_2-eq	%	Gg CO_2-eq	%	Gg CO_2-eq	%	Gg CO_2-eq
2008	1064.3	93.3	3.7	0.3	2.9	0.3	69.9	6.1	0.30	0.03	1141.1
2009	1064.8	93.4	4.1	0.4	1.3	0.1	69.2	6.1	0.23	0.02	1136.8
2010	1056.5	93.5	6.7	0.6	1.3	0.1	65.5	5.8	0.02	0.00	1130.1
2011	1102.9	93.8	4.9	0.4	1.3	0.1	66.3	5.6	0.02	0.00	1175.4
2012	1111.4	93.4	10.3	0.9	1.3	0.1	66.2	5.6	0.02	0.00	1189.3
2013	1095.8	91.4	35.0	2.9	1.3	0.1	66.5	5.5	0.02	0.00	1198.7
2014	1096.8	93.4	9.5	0.8	1.3	0.1	67.2	5.7	0.02	0.00	1174.9
2015	1107.0	93.6	6.8	0.6	1.3	0.1	67.8	5.8	0.02	0.00	1183.0
2016	1110.5	93.5	6.8	0.6	1.3	0.1	68.5	5.8	0.02	0.00	1187.3

The GHG emitted in the Canary Islands environmental complexes from MSW were 1110 Gg of CO_2-eq. Biological treatment of solid waste produced 6.8 Gg of CO_2-eq, wastewater treatment 68.5 Gg of CO_2-eq, waste incineration 1.3 Gg CO_2-eq, and other activities 0.02 Gg CO_2-eq. These figures indicate a 0.4% increase in total emissions compared to 2015.

Emissions of gases produced by MSW deposited in the environmental complexes of the Canary Islands have thus undergone considerable growth, acquiring significant weight in the overall total. Although more detail will be presented later, the data provided in Table 1 show that such growth in recent years is paradoxically driven partly by better waste management. This reflects a transition from lack of control to better supervision and disposal in well-organized facilities. In turn, this implies greater local methane emissions from decomposition of buried organic waste. In fact, the most important GHG within environmental complexes is methane (93.5%), while CO_2 emission is practically testimonial. Most of the latter, either by gasification and direct emission or by incineration of methane, can be considered to derive from biomass and is therefore neutral regarding this gas. Graphing these data, Figure 2 illustrates how there has been a marked continuous growth up to 2016 in the total emissions of the sector, although it has been less pronounced in recent years. The same trend is seen in landfill disposal.

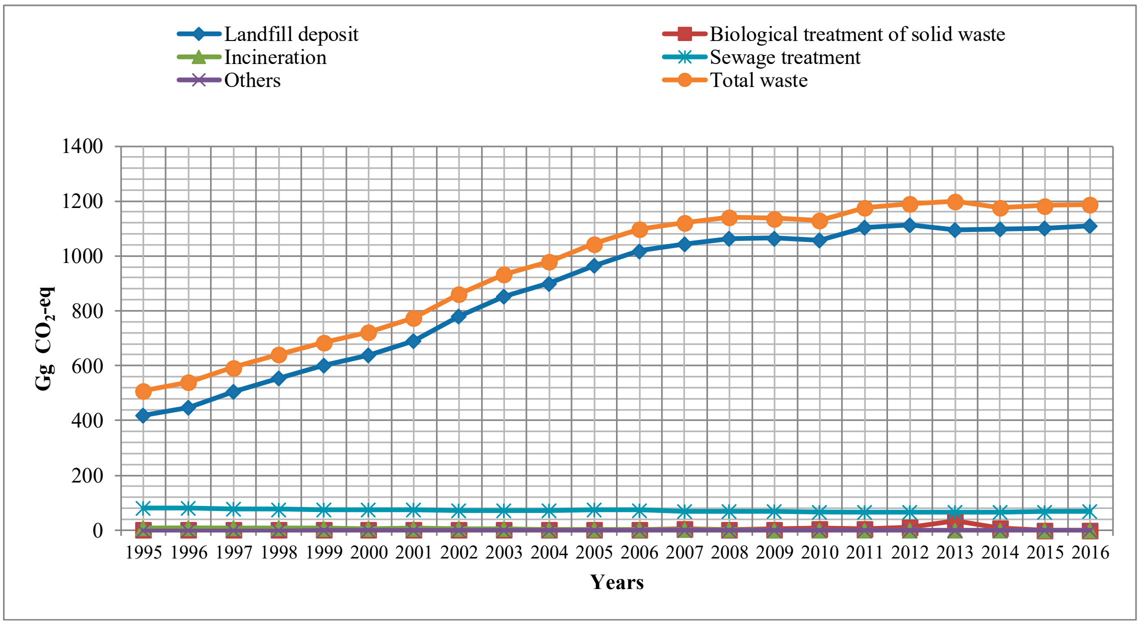

Figure 2. Recent history of GHG emissions due to treatment and waste disposal in the Canary Islands (authors).

3. Case Study: Waste Management in La Gomera

3.1. The Management of Municipal Solid Waste in La Gomera

La Gomera is located approximately 28 km from the west coast of the island of Tenerife (see Figure 3). It has an area of 369 km^2, making it the third smallest inhabited island in the Canary archipelago after El Hierro and La Graciosa.

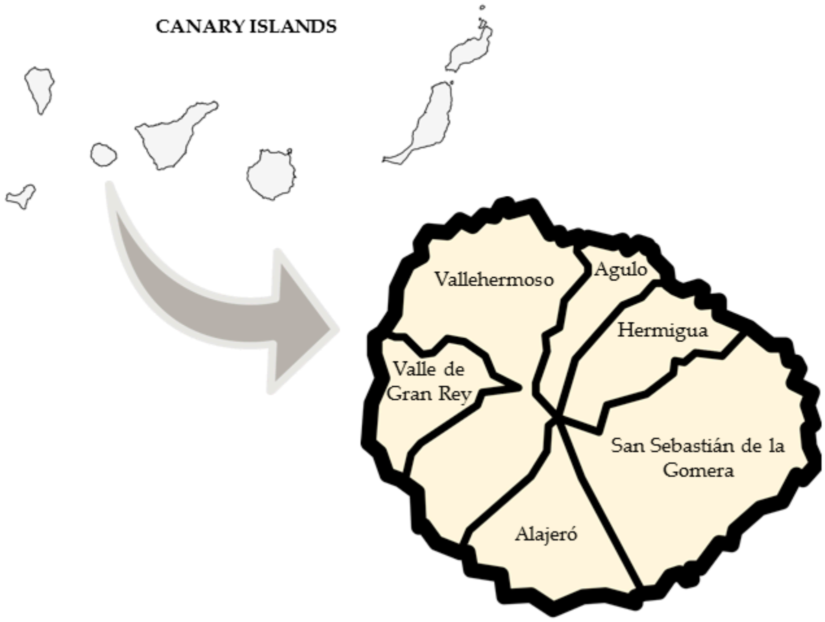

Figure 3. Location and boundaries of the 6 municipalities of La Gomera.

In 1960, La Gomera had a population of approximately 30,000 inhabitants. From then on, the population began to decrease progressively, reaching a minimum of about 15,000. However, in recent years its population has grown, reaching 21,136 inhabitants in the year 2018 [37].

However, this figure corresponds only to the permanent population and would be too simple an approximation to study the real waste stream of the island. In this study, we work with the equivalent population, which also takes into account the stationary population and the tourist population. Specifically, the value of the equivalent population for the year 2018 is 27,776 inhabitants.

The Master Plan for waste management on the island is obsolete [38]. This plan is awaiting an update that to date has not been realized. Few islands in the Canary archipelago have an updated waste management plan. Meanwhile, the islands resort to the Canary Islands Comprehensive Waste Plan, approved by Decree 161/2001 [39].

Waste collection forecasts estimate low quantities to propose a processing plan that requires costly and complicated treatment. In fact, compost production for direct use in agriculture or gardening would in principle be more useful than energy production utilizing organic waste from domestic, agricultural, forestry and sewage sources, etc. However, disposal of such waste in landfills or the sea should be abandoned and permitted only as a last resort. At the same time, transporting waste long distances is no solution, due to the energy consumption involved and resultant environmental/GHG impact. Based on the data collected and the publications available [20], the total amount of bulk refuse that could classify as MSW produced on La Gomera is close to 9709 tons per year. The current management system is based on simple removal of these quantities to landfill site. From the energy and environmental point of view, this solution can be vastly improved. In addition, the quantities destined to recycling are minimal or symbolic because the selective collection system on the island is not fully implemented. Addressing the current European directive [40] transposed to Spanish legislation by the Royal Decree 1481/01 [41], which regulates waste disposal in landfills, it is clearly necessary to progressively reduce the amount of biodegradable municipal waste destined to landfills.

La Gomera has ten waste-disposal sites. Five dumping areas for uncontrolled municipal waste (one of them abandoned more than ten years ago), an uncontrolled inert landfill, three centres for storing scrap metal, a "clean point" recycling depot (in the capital, San Sebastián) and an environmental complex. This facility is located within the municipal district of San Sebastián, in the Revolcadero ravine. It has an impermeabilized base. However, the major problem is that it is close to overflowing, due to the absence of efficient waste prevention and management policies. In addition, it has suffered several serious fires. Up to 2013, there have been several outbreaks and hot zones in the oldest part of it. These have also caused serious environmental impact of the surrounding environment.

The current model prompted the need to examine the state of the landfill to find out if it can be improved. In particular, the authorities wished to investigate if it is possible to rehabilitate the landfill and recondition it as a green space. According to data from the environmental department of La Gomera island council [42], the authorized discharge volume is about 236,605 m^3. In contrast to the 2010 data, it is necessary to point out that due to growth in tourism, the MSW flow is increasing considerably. The figures speak of up to 20.6%, reaching 15,000 tons per year.

Summarizing, in La Gomera, like in most of the Canary Islands, waste management is a process that requires serious study by enterprises, public organisms, and political forces present in these territories. Currently, the process is linear. Goods are imported (occasionally produced), used and discarded. How are they discarded? At present, only 5% of the MSW collected is treated in recycling plants. The rest, the so-called "black bag" is buried in the landfill zone of the only environmental complex functioning on the island. This leads to the inevitable need to expand its capacity from time to time. The implications are clear: inefficiency in MSW management processes, generation of polluting landfill gases and liquids, non-compliance with European policies and objectives on waste, contamination and destruction of natural areas and, among others, increased waste transportation and storage costs.

3.2. Treatment and Characterization of the Study Samples

The last official update on the composition and characterization of MSW in the Canary Islands was provided by their autonomous government [20]. The authors rely on this study to better understand the management options and potential waste treatments on the island of La Gomera. Regarding the sampling quantities, from trucks and loaders, representative samples were obtained whose weight ranged between 200 and 300 kg. For each sample, a tally register file and data tables were established and completed. Thus, on La Gomera, six significant samples were taken (one for each municipality). Table 2 shows the composition obtained on averaging the samples cited. Of these samples, 32.4% was the organic fraction and 40.2% the rest of the waste that is not classified as packaging (plastics, glass, iron, etc.). These data are important to redesign waste management at the island level.

Table 2. Composition of waste samples on the island of La Gomera.

Fractions	Typology	Kg	%	Relative %
Organic fraction	<25 mm	22.0	9.5	29.3
	25 < x < 80 mm	16.3	7.1	21.8
	>80 mm	15.9	6.9	21.2
	Plant-origin residues	20.8	9.0	27.7
Total organic fraction		75.1	32.4	100
Paper and cardboard	Paper	15.3	6.6	53.5
	Cardboard	13.3	5.7	46.5

Table 2. *Cont.*

Fractions	Typology	Kg	%	Relative %
Total paper and carboard		28.6	12.3	100
Packaging	Low Density Polyethylene	15.9	6.9	45.8
	Bricks	4.8	2.1	13.8
	Ferrous	2.2	1.0	6.4
	Non-ferrous	1.8	0.8	5.3
	Polyethylene Terephthalate	1.6	0.7	4.6
	White High Density Polyethylene	1.7	0.7	4.8
	Coloured High Density Polyethylen	1.2	0.5	3.6
	PVC	0.0	0.0	0.1
	Other plastics	1.0	0.5	3.0
	Glass	3.0	1.3	8.6
	Wood	1.4	0.6	4.2
Total packaging		34.7	15.0	100
Non-packaging	Plastics	11.1	4.8	11.9
	Ferrous	7.4	3.2	8.0
	Non-ferrous	3.7	1.6	4.0
	Glass	0.0	0.0	0.0
	Other	28.0	12.1	30.1
	Textiles	17.4	7.5	18.7
	Rubber and leather	1.1	0.5	1.2
	Wood	14.8	6.4	15.9
	Sanitary/Hygienic	2.7	1.1	2.9
	Waste Electrical and Electronic Equipment	4.4	1.9	4.7
	Inert	2.7	1.2	2.9
Total non-packaging		93.2	40.2	100

For the granulometry tests, once the sample was weighed, the granulometric separation of the waste was carried out by screening. Two screenings were carried out, one at 80 mm with an electric rotating screen (trommel to scale) and a second screen with 25 mm flat screen. The waste is therefore classified into three fractions: greater than 80 mm, less than 25 mm and intermediate fraction between 80 and 25 mm. Screening by electrical machinery has meant a much more efficient classification of these fractions, later facilitating the classification of each of them.

Regarding the waste triage, once the granulometry measurement has been finished, we proceeded to classify the three fractions mentioned above according to the characterization parameters of Table 2.

4. Material and Methods

4.1. The Model

In Figure 4, a description of the proposed model is provided. In addition to the island being thus able to comprehensively manage its waste, the aim is to reduce the surface area occupied by the landfill by almost 90%. In this way, repopulation and soil treatment work and landscaping can facilitate the environmental recovery of the area. This, without doubt, will contribute to the restoration of the native ecosystems with the introduction of local flora and fauna in order to reintegrate the landfill area into the landscape.

The current process of waste management is linear and is nothing more than depositing the MSW in the landfill, after separation of 5% for recycling. The new circular economy model consists of implementing a gasification process to valorize the daily and accumulated waste stream in the landfill until now. The fractions shown in Figure 4 are estimates that have been made with the technologists' pilot tests. Then, the process has two parts: on the one hand, both waste streams (landfill and MSW) go through a separation and treatment process, through which solid recovered (SRF) is obtained, coming from the organic and inorganic fraction. It is then gasified to convert it into electrical energy or thermal energy.

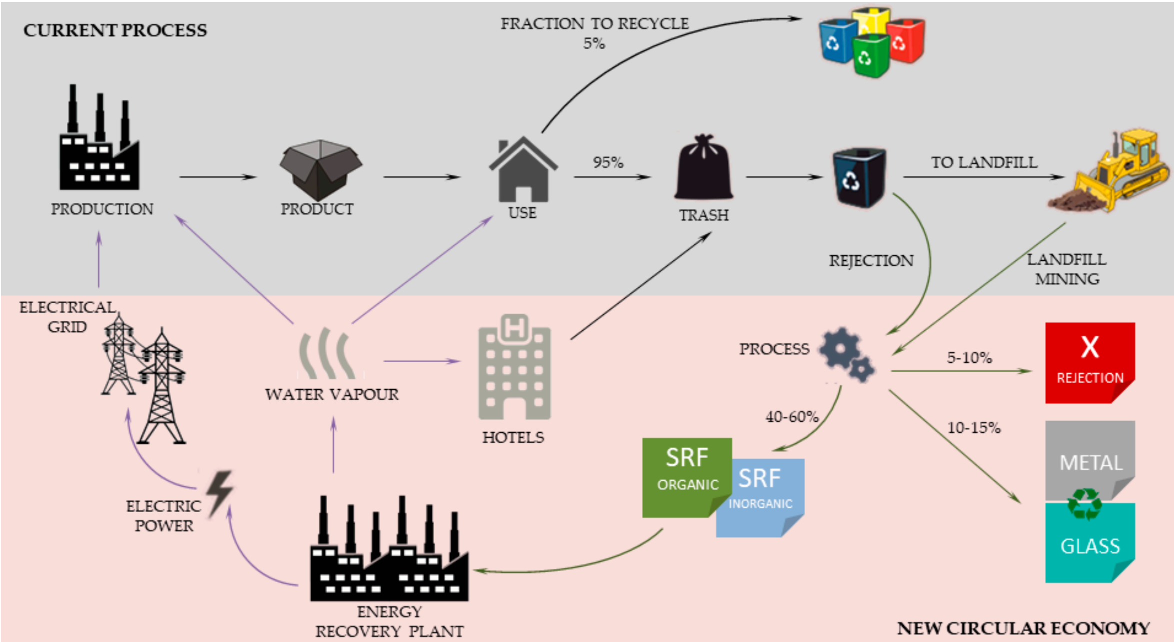

Figure 4. Flow diagram of the waste energy recovery process proposed for La Gomera.

Each of the fractions represented are in proportions identified by the characterization work previously mentioned. In this way, a plant with machinery arranged in modules is proposed, in order to occupy the smallest space possible, at most an area of 6000 m^2. Therefore, the proposal consists of implementing a separation and treatment process adapted to smaller flows and modular arrangement to minimize the space occupied. The island would be autonomous in terms of its waste management, without needing to transport it to other treatment centres. In addition to valorizing the waste by transforming it into gasified fuel, to generate electricity and considerably reduce the energy costs on the island. It must be emphasized that it is not an incineration process with the air pollution that it entails. This means it is possible to implement a new electricity generation plant that consumes fuel produced from material unsuitable for recycling that is extracted from the MSW stream. It can be situated at a strategic point for maximum utility, preferably in the area close to most demand.

The amount of annual waste considered here is that provided by the island council. According to these data, the waste generated is around 11,900–12,650 tons per year. However, the records show that there are years (e.g., 2011) in which, due to expanding tourism on the island, it can reach 15,000 tons per year. In this context, there is a 'wasted' flow of waste from which no benefit has been derived.

Indeed, valuable available resources are not being used, with the amounts destined for minimum recycling. On the other hand, addressing the current European directive [40], it is necessary to take into account the need to progressively reduce the amounts of biodegradable municipal waste assigned for landfill. Based on this goal, it is proposed that a process be implemented to solve the current situation of the island, which can in turn be extrapolated to other similar environments, maximizing the quantity of waste destined for reuse and recycling. In addition, the unusable flow is also valorized and put to use in order to minimize spilling waste.

Likewise, with the aim of contributing to environmental improvement, landfill-mining operations are proposed for emptying the landfill, to recondition and replanting the area with appropriate vegetation until it regains its previous ecological value. In the study carried out, the waste it harbours can be progressively treated in the same plant where the MSW flow of the regular collection is treated.

Therefore, the objective of this processing plant would be to manage all the solid waste produced in La Gomera.

4.2. Calculation of Landfill Emissions

The theoretical model we apply to calculate CH_4 emissions in a landfill with uncontrolled emissions is based on the following first-order kinetic equation:

$$Q_{CH4} = L_o \cdot R \cdot (e^{-kC} - e^{-kt}) \quad (1)$$

where: Q_{CH4} is the amount of methane at time t (Tn/year); L_o is the methane generation potential (Tn Q_{CH4}/Tn waste); R is the annual average amount of solid waste (Tn waste/year); k is the ratio of methane generation (1/year); C is the time since the closure of the dump or landfill (years); t is the number of years since the first load was deposited.

In this case, the methane generation ratio (k) takes a value of 0.04 for the climate of the area, according to the IPCC. The time of closure of the landfill is zero (it is still active). Likewise, the time since the first deposition dates corresponds to a value of 14 years.

Additionally, to calculate Lo the following formula is applied:

$$L_o = DOC \cdot DOCf \cdot s \cdot F \cdot MCF \quad (2)$$

where: DOC is the fraction of degradable organic carbon in the refuse (dimensionless); DOCf is the portion of DOC converted to landfill gas (dimensionless); s takes the value of 16/12 (stoichiometric factor to convert carbon to CH_4, dimensionless); F is the fraction of CH_4 in the landfill gas (dimensionless); MCF is the methane correction factor indicating the amount of methane in landfill gas (dimensionless). In this case, unity is assumed as its value (one managed landfill).

Since not all organic matter can be decomposed, the DOC fraction considers the fraction of organic carbon accessible to biochemical decomposition, depending on the content of the waste, which varies according to its place of origin [43]. This study takes into account the variability of the data on this, as well as its possible range. The DOC is expressed in Equation (3) and is essential to calculate methane generation.

$$DOC = 0.4 \cdot A + 0.17 \cdot B + 0.15 \cdot C + 0.30 \cdot D \quad (3)$$

where A is the proportion of carbon in the paper, cardboard and textile content (%); B is the carbon corresponding to putrescible organic waste from gardens, parks etc., except food (%); C is the carbon in food waste (%); D is the carbon in wood and straw waste (%).

In a landfill, only a fraction of the DOC is actually decomposed under anaerobic conditions (DOCf) and converted to CH_4 and CO_2. The rest remains in the landfill as stable organic matter or is degraded through other processes. In this study, a default DOCf value of 0.5 was considered, as recommended by the IPCC based on several experimental studies [36,44] as is the value 0.5 assumed for the methane fraction in landfill gas (F).

4.3. Estimation of the Future Population in La Gomera

The hypotheses about the future evolution of the three demographic phenomena that are part of the growth of the population (birth, mortality and migration), are established from the figures observed for each of them. For births and deaths, the figures of the Natural Population Movement have been used. The population of departure, by sex and age, has been obtained by softening the data of the census. Future births have been calculated from projected fertility rates starting from those observed in the years 2002 to 2004, while mortality rates have been calculated by applying annual improvement coefficients. For migratory movements, the hypotheses are established from the data observed in the Residential Variation Statistics obtained from the variations registered in the census of the National Institute of Statistics.

Therefore, as explained in Section 3, in order to carry out the population estimates, the permanent population has been taken into account, as well as the seasonal population corresponding to the occupation of secondary dwellings, and the tourist population.

The seasonal population of secondary dwellings is estimated according to the days of stay per year and number of inhabitants per dwelling. According to the available data, an employment rate in the secondary dwellings equal to that of the main dwellings (inhabitants per dwelling) was used as a calculation hypothesis, and an average stay period of 60 days was considered. The equivalent tourist population is obtained from the registered sectorial data, whose sources come from the Canary Institute of Statistics and from the Ministry of Tourism, Culture and Sports of the Canary Islands Government. These data are combined according to the following formula to obtain said equivalent population (see Equation (4)).

$$H_{eq} = n \times D \quad (4)$$

where n is the number of tourist places and D the degree of occupation.

Therefore, Table 3 shows the estimated equivalent population for the period between 2016 and 2025.

Table 3. Population estimation of the island of La Gomera 2016–2025.

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Population	26,908	27,340	27,776	28,211	28,641	29,078	29,510	29,938	30,369	30,794

4.4. Estimation of the Energy Generated by the Waste Stream

The last estimated volume occupied by MSW was 227,500 m^3. With the tests carried out and according to the samples and data of the local authorities de La Gomera [20], an average density for this waste of about 650 kg/m^3 was assumed for the present study. In addition, according to the studies of recyclable waste in the landfill of La Gomera, and also the technologist with whom the estimation model was constructed [45], it is estimated that this facility contains about 40% soil-type material, 40% suitable for fuel, between 10–15% that can be recycled (metals and glass) and 5–10% to be rejected. Table 4 shows the estimation of MSW generated up to 2025, with its fractions destined to recycling, rejection, and fuel to be converted into energy (Solid Recovered Fuel). A quantity of 147,875 tons could be considered the landfill waste for annual use. However, as shown in Table 5, this amount should be deducted from the high proportion of soil and aggregates that it also contains.

Table 4. Estimation of municipal solid waste for the island of La Gomera 2016–2025 (in tons).

		Year										
Processed Flow	**Percentage (%)**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**Total**
Fraction to recycle	30	3442.18	3497.44	3553.22	3608.86	3663.87	3719.77	3775.03	3829.78	3884.92	3639.29	36,614.36
Fraction rejected	10	1147.39	1165.81	1184.40	1202.95	1221.29	1239.93	1258.34	1276.60	1294.97	1213.10	12,204.79
Energy fuel	60	6884.35	6994.88	7106.43	7217.73	7327.74	7439.54	7550.06	7659.58	7769.85	7278.58	73,228.73
TOTAL	100	11,473.92	11,658.13	11,844.05	12,029.54	12,212.9	12,399.24	12,583.43	12,765.96	12,949.74	12,130.97	122,047.88

Table 5. Characteristics of landfill waste on the island of La Gomera.

Waste Stream	**Density (kg/m^3)**	**Volume (m^3)**	**Quantity (Tn)**	**Quantity per Year (Tn/Year)**
Landfill waste	650.00	227,500	147,875	-
Processed flow		Percentage (%)	Quantity (Tn)	Quantity per year (Tn/year)
Soil and aggregates		40	59,150.00	5915.00
Fraction to recycle		10	14,787.50	1478.75
Fraction rejected		8	11,830.00	1183.00
Energy fuel		42	62,107.50	6210.75
TOTAL		**100**	**147,875.00**	**14,787.00**

5. Results

Figure 5 is a diagram of the energy conversion process and its contribution to the overall energy framework of the island. It shows that the energy produced from waste is in no way negligible. It would moreover constitute a different energy source from the diesel engines that to date still provide most of the electricity in the energy mix consumed on the island. According to data from the Spanish Electricity System Operator [46], the average price of electricity generation on La Gomera during 2018 was 215.35 €/MWh. There is no doubt that the approximately 26,000 MWh generated per year by this re-utilization system would help ease the heavy electricity bill in this island subsystem.

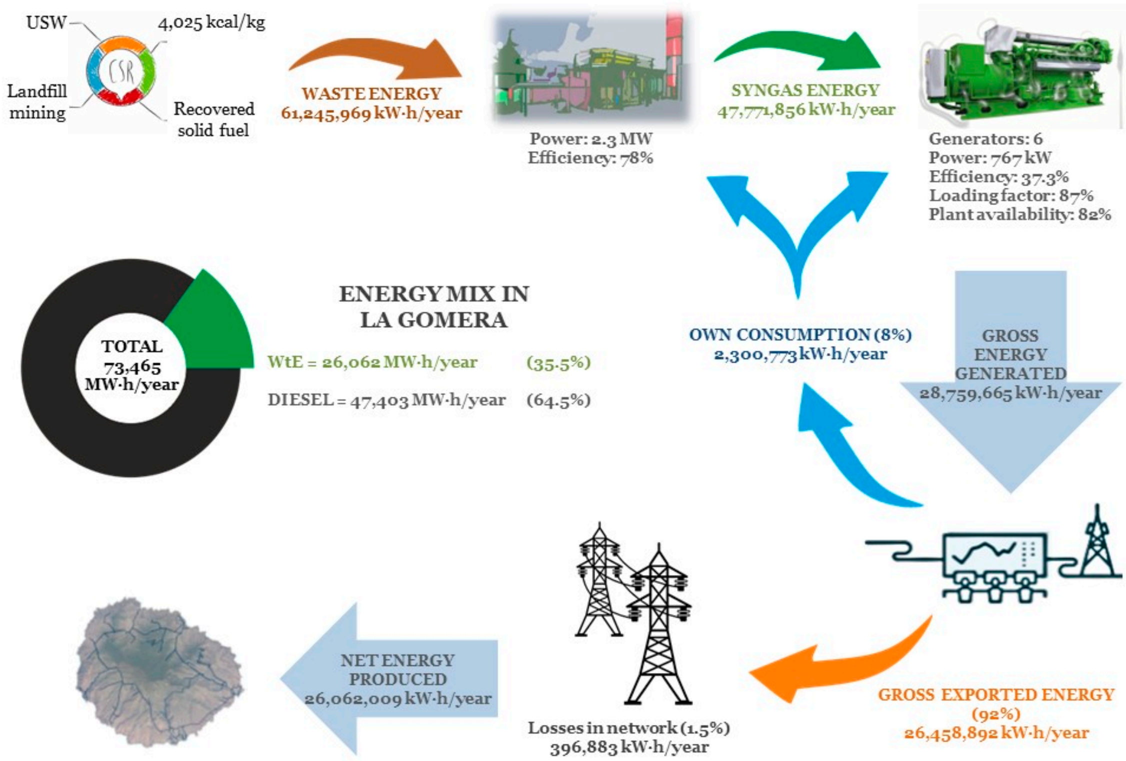

Figure 5. Proposed diagram of waste energy recovery for La Gomera.

In Figures 6 and 7, it is possible to compare the evolution of waste management and the energy contribution to the island for the 2016–2025 period. Figure 6 shows that waste valorization permits better recycling figures than those achieved with the previous management policies. Although, as mentioned before, energy recovery is not the first step of the European waste policy, there is no doubt that, given the characteristics of the archipelago, it is a solution that significantly improves the rate of recycling, reduces landfilling and, in addition, it contributes with a significant energy generation.

Finally, Figure 8 shows the emissions of CH_4 and CO_2 within the proposed horizon that would be avoided by landfill mining. That is, the figures shown correspond to what the MSW collected and landfilled in the current situation would generate annually.

The results obtained are encouraging. On the one hand, the share of the renewable resource increases up to 35.5% (almost 6 MW per year). This has two advantages: the first one is to reduce the contribution of fossil fuel and the second one, a renewable resource of a manageable nature is considered (a matter of vital importance in these isolated environments). On the other hand, the fraction that is recycled is increased by around 10–15%. And, finally, GHG emissions are reduced considerably (see Figure 8) with the implementation of this model.

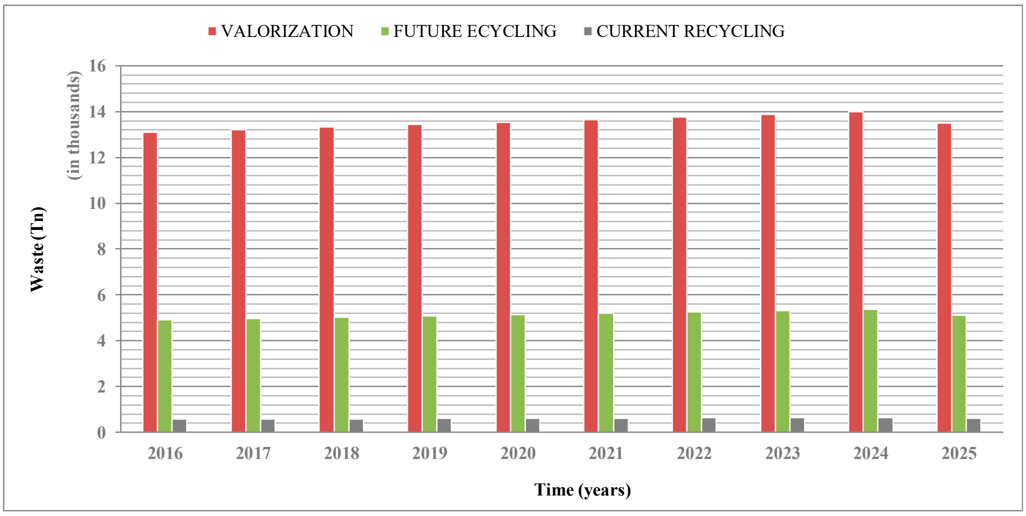

Figure 6. Recycling level for the horizon 2016–2025.

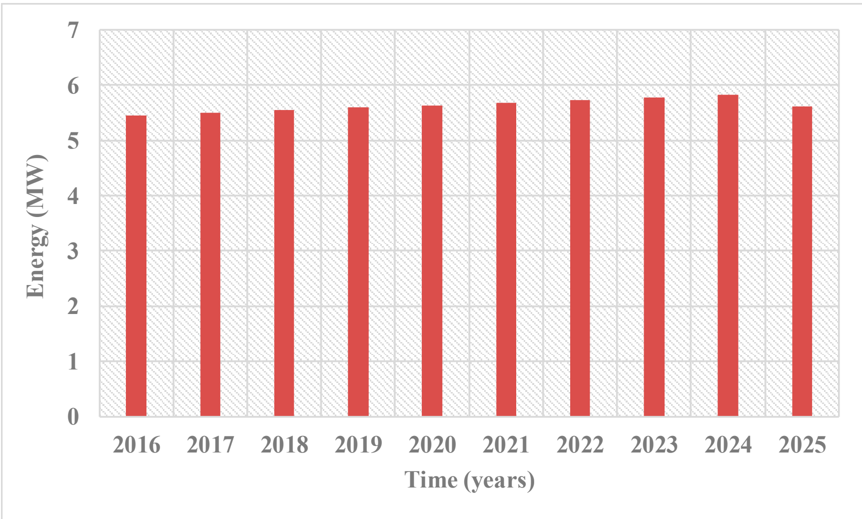

Figure 7. Valorization level for the horizon 2016–2025.

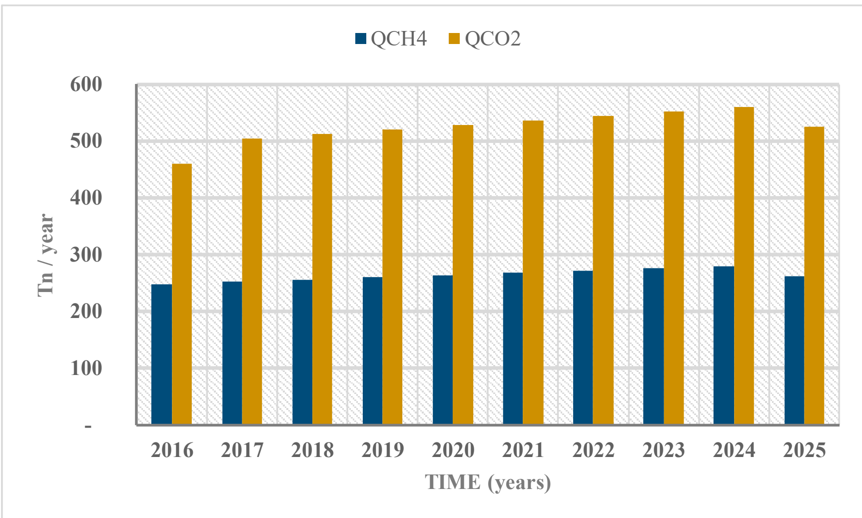

Figure 8. Evolution of CO_2 and CH_4 emissions on the island of La Gomera 2016–2025 (without implementing model).

6. Discussion

First, as in the case of energy, it is important to describe the specific policies and regulations governing waste in these small isolated systems. This denomination, within the Spanish framework, refers to all the electrical subsystems of the Balearic Islands and the Canary Islands, as well as the autonomous cities of Ceuta and Melilla situated on the coast of Morocco. As explain by Uche-Soria and Rodríguez-Monroy [47], given their isolated nature and their small size, the non-mainland electricity systems (NMS) have their own limitations and constraints that not only affect electricity supply, but also the efficient management of energy generation and treatment of municipal waste. These peculiarities result in investment and exploitation costs being higher than those of an interconnected continental system.

Second, special problems arise in waste management on islands around the world [48]. In fact, the peculiarities of these territories impede the collection, transport, storage, treatment and disposal of waste to a large extent. This entails high management costs, aggravated by the need to transfer the waste to and from remote areas. In particular, the disposal facilities and infrastructure are insufficient, and the fluctuating impact of tourism is rarely taken into account in planning their dimensions. In addition, due to the peculiarity of protected ecosystems, it is not easy to obtain landfill sites or achieve adequate economies of scale for the real needs. As an example, it turns out that in these territories electricity generation costs are higher at night, when demand is low, unlike in continental systems. This is due to the efficiency of large generator turbines being lower when operating during valley demand. The case of solid waste management can be extrapolated from this situation. Smaller flows and scarce investment in efficient waste management policies mean that the cost of management, treatment and valorization is greater than in other environments.

Third, recently, Ramos-Suárez et al. [49] elaborated a study on the production of biogas from animal manure produced on farms in the Canary Islands. With the data they produce, it can represent an additional source of energy to generate heat and electricity. With a total production of nearly 500,000 tons of manure per year, the potential for biogas can reach 27.1M m^3/year, with an equivalent installed capacity of 6.8 MWe. In this regard, the potential GHG emission savings due to the production of biogas from animal manure annually could reach more than 55,000 tons of equivalent carbon dioxide. It is true that several experiments and pilot schemes have been under way for a long time in other European islands [50]. Indeed, the results show that it is possible to improve waste management performance at a reasonable cost. Jofra et al. [51] provide various ideas, from the implementation of waste collection and management systems to the adjustment of waste generation rates.

Fourth, although they can become economically profitable activities, there is a lack of reliable management and processing services and data in agricultural and forestry waste processing. Nevertheless, abundant waste results from the banana and tomato production enterprises, etc., that prevail in these environments. This is probably due to a combination of lack of knowledge, scarce research due to insufficient funding and a persisting lack of environmental education and culture regarding the need for sustainability and circular economy [52].

Fifth, according to the latest data published by the Government of the Canary Islands [53], since 2008 there has been a single biogas plant that processes part of the solid municipal waste handled at the Arico Environmental Complex on the island of Tenerife. The installed capacity of this installation is 1.6 MW and during 2017, it injected 8915 MWh into the electricity grid, which was an increase of 1% over the previous year. In addition, Zonzamas biomethanization plant in the island of Lanzarote has two generator turbines of 1048 MW each and began to supply electricity to the grid in 2013. During 2017, the plant produced a net 588 MWh, 15.1% more than the previous year. Therefore, for the Canary Islands, electricity production through this source of energy in 2017 was 9502 MWh, 1.8% higher than in 2016 (see Figure 9). Despite this increase, the Canary Islands continues to be ranked in a low position regarding the use of this resource and, therefore, a change of mentality is needed to address new challenges.

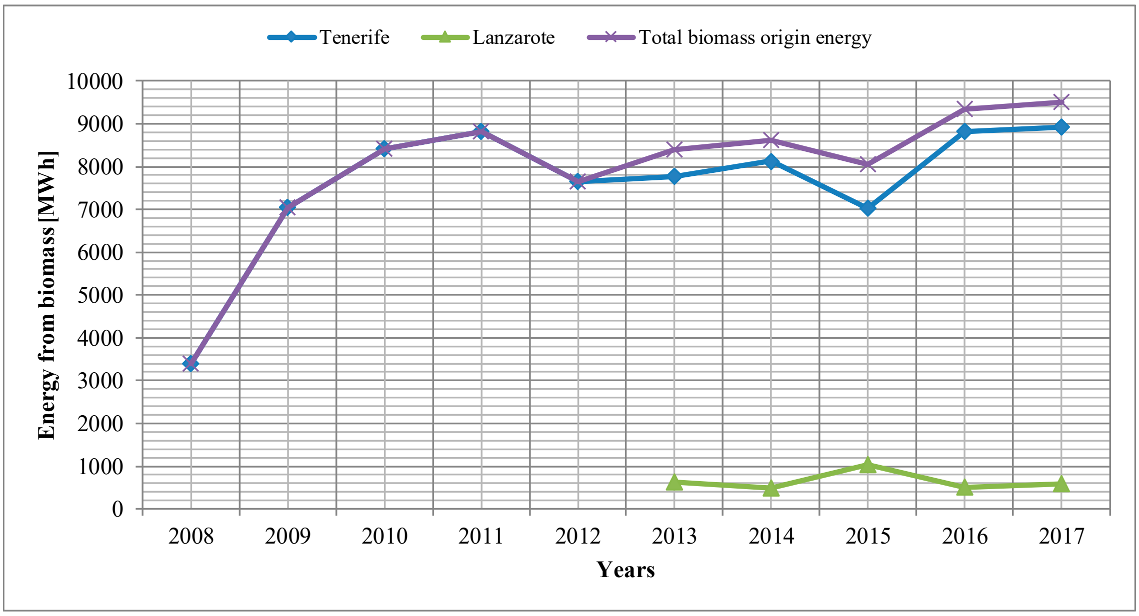

Figure 9. Annual variation in energy production from biomass.

Sixth, the Canary Islands have great potential for progress towards a circular economy. The archipelago has a historical commitment to sustainability, has excellent benchmarks (each island is different) and is a magnificent showcase for transferring sustainable technology to regions such as Africa [54]. At present, in the Canary Islands there are several R&D&I projects under way, as well as initiatives in sectors such as microalgal biotechnology (linked to the emerging blue economy sector). However, these isolated oceanic environments are still far from European waste targets.

Seventh, the limiting characteristics of the territory greatly impede the activities of collection, transport, storage, treatment and disposal of waste and involve high management costs, aggravated by the need to transport the waste to and from remote areas. The common problems in isolated territories are the following: small number of facilities for treatment or elimination, impact of tourism on the local waste management plan, the limited space available to locate landfills and their rapid filling, and the difficulty of achieving economies of scale. The management of municipal solid waste on the island of La Gomera and in the rest of the Canary archipelago continues to depend almost exclusively on landfills. This degrades natural resources and produces emissions of methane gas (CH_4), a more potent greenhouse gas than carbon dioxide (CO_2) [55]. Facing this same fact, Tan et al. [56] carry out a study in Malaysia from the energy, economic and environmental point of view on the possible solutions for the energetic use of waste. In the case of La Gomera, the composition of the waste and the peculiarities of the environment greatly reduce the technologies. However, a study in collaboration with public institutions to address technological solutions for the whole archipelago is still missing. To achieve this, the material properties of the MSW, their energy conversion potential, their composition and greenhouse gas (GHG) emissions, provide valuable information to make decisions in the management policies of MSW.

Eighth, the main contribution of this study is to show that, despite the singularities of the isolated environments, it is possible to achieve a sustainable management of the MSW for the benefit of the Waste Management Plan, the island's energy mix and the environment. In the case of the island of La Gomera, due to the typology of MSW (physical-chemical characteristics and quantities), a viable process is the gasification and conversion into energy through SRF. However, the authors consider the interest in comparing this study with other subsystems, for example, the rest of the islands of this archipelago or other similar environments such as the Azores Islands or the Cape Verde archipelago. Regarding the limitations of this study, the tests are carried out in pilot plants and real monitoring would be desirable.

Likewise, another limitation that the authors find to implement this energy management model is the short-term vision of the actors involved in the energy planning of these regions.

7. Conclusions

It should be noted that waste management is a media issue, in which the fear of contamination is very high. In isolated environments, the transfer of waste to other regions is not a solution: neither optimal nor feasible. As in other works cited in the previous sections, here we show how a solution based on a WtE plant contributes to reducing GHG emissions, increases the rate of recycling and treats waste in a sustainable manner. Based on this, in isolated environments, energy recovery is a good and sustainable alternative to landfill.

On the other hand, it is vital to implement waste policies that are aimed at not only improving the integral management of MSW, but to urgently set goals that have been delayed for many years. These targets will contribute to improving and materializing the concept of sustainability in these environments. In this sense, the insularity of municipal waste management (collection, transport, treatment, recycling and disposal), recovery of hazardous materials from municipal waste, recovery and valorization of those waste fractions feasible from a unified technical, economic and environmental perspective, implementation of communication and training campaigns, etc., are all pending issues that must not be forgotten. All this would be more effective if sustainability were understood as the key from the very beginning of the production chain (sustainable design). In this way, besides Waste to Energy (WtE), there would be also Waste to Material (WtM)-type solutions.

Within this landfill-mining concept, it must be pointed out that materials recovered deposited in landfills should be grouped for later reuse as secondary materials, and if impossible, their energy recovery. A specific example are the scrap and precious metals obtained from the process. These have a lower market value than in their new unused state, especially in the case of those most sensitive to degradation. However, the local recovery of these materials would to a certain degree alleviate the heavy cost of exporting them and importing new raw materials.

Finally, the authors have tried to put forward a solution that takes into account the circular economy model as a self-regenerative system in which the input of waste resources and emissions and energy losses are minimized by slowing, closing and reducing the material and energy loops. It is obvious that the road is still arduous and that isolated environments are still behind continental systems, but at this point it is essential to propose studies and measures that encourage awareness and action.

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